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14. ABSTRACT
This report describes the technical progress towards the development of signed processing algorithms for hybrid lidar- radar designed to improve detection performance.

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Technical Section

Technical Objectives

The technical objective of this project is the development and evaluation of various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance. Practical algorithms must be developed taking into account the underwater propagation channel and the processing requirements for each algorithm as shown in Figure 1.

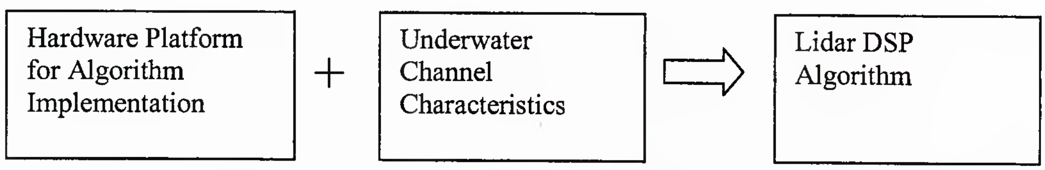

Figure 1. The development of lidar DSP algorithms must take into account hardware implementation and underwater channel characteristics.

Technical Approach

A significant challenge in hybrid lidar-radar is optical absorption and scattering. The absorption of the light photons by the molecules in the water channel contributes to a decrease in the total signal level collected at the receiver. This unwanted phenomenon can be reduced by selecting the wavelength of the laser light to be in the blue-green region. Backscattering occurs when transmitted light signal reflects off a water particulate and reaches the detector without first reaching the object. Thus, backscattered light contains no information regarding the object and it reduces the image contrast and resolution as well as the object ranging measurement accuracy. There have been various methods that attempt to reduce the backscatter. One method is to increase the modulation frequency beyond 100MHz and another is to use a dual high-frequency (>100MHz) approach that uses high speed modulation to help suppress backscatter while also providing an unambiguous range measurement. In general, it is desired to determine which combination of Radio Frequency (RF) modulation frequencies, modulation waveforms, and signal processing algorithms help improve hybrid lidar-radar performance in a variety of underwater environments.

The approach is to focus on the optical proximity detector that is being developed with ONR funding. The goal is to replace analog hardware with digital components to benefit from the advantages offered with digital hardware and signal processing, including better sensitivity due to large dynamic range digitizers and lossless digital demodulation and filtering, reconfigurability via software to improve sensor

adaptability in different environments and for multiple applications, and real-time processing for instant feedback.

Progress Statement Summary

In FY12 we developed a new backscatter reduction technique that leverages spatial filtering techniques used in through the wall imaging (TTWI) radar. The technique was validated using both simulated and experimental data. Simulated data was generated using Rangefinder, a lidar simulation tool developed by the Navy. This data was then processed using the spatial filter and ranging performance between the filtered and unfiltered data were compared. In addition, experimental ranging data taken in a Navy test tank were also used to validate the filter and ranging measurement results with and without the application of the spatial filter in order to compare the performance improvements that can be obtained for various turbidities and laser modulation frequencies. The work showed significant promise was published and presented at the Oceans 2012 conference and additional theoretical and simulation work was performed to better quantify optimal delay requirements as a function of turbidity. Specifically, improvements on the order of 7 and 11 attenuation lengths are predicted through simulation when spatial filtering is applied to CW and dual-tone ranging, respectively. Application of the technique to experimental data showed only modest results; however, the experimental data did not include ranges that were long enough to test the algorithm. Dr. Linda Mullen's group at NAVAIR has performed additional experiments to validate the technique and their results are included in a recent journal article [1].

In FY13, a new ranging approach using a combination of frequency-domain reflectometry (FDR) and blind signal separation (BSS) was developed that allows for automatic target detection at long unambiguous ranges. FDR was originally developed in the 1980s for the purpose of approximating the location of faults in long fiber optic cables. This method has been shown to simultaneously achieve high range precision and long unambiguous ranging. The technique was simulated as a function of water turbidity using Rangefinder. In BSS, data are transformed into a statistical domain in which signals are separated based on their statistical properties. This technique is used to discriminate between the target return and backscatter. Used in conjunction with the FDR technique the blind signal separation was shown to provide an order of magnitude (x10) reduction in backscatter using Rangefinder simulation resulting in an automatic target detection improvement of 14 attenuation lengths. These simulated predictions were published and presented at the Oceans 2013 conference.

In FY14, experiments were performed using a test tank at NAVAIR to validate the performance of the FDR ranging and BSS backscatter suppression techniques, and to explore performance of the dual-tone ranging approach using higher frequencies than had been previously investigated. Experimental results for FDR and high frequency dual-tone ranging were published and presented at the SPIE DSS 2014 conference. Increasing modulation frequency by 200 MHz above previous values for the dual-tone technique was found to offer a modest performance increase of about one attenuation length for a maximum operating range of about six attenuation lengths. FDR experimental results showed performance out to 10.2 attenuation lengths before the technique was no longer able to detect the target. Experimental results for BSS applied to FDR were published and presented at the Oceans 2014 conference; this presentation received second place in the student competition at this conference. The FDR/BSS experiments demonstrated increased ability to discriminate between the target return and backscatter, extending ranging performance to 14.7 attenuation lengths. This is almost three times the detection range obtained in previous work with the single- and dual-tone approaches. Preliminary

[1] R.W. Lee, A. Laux, and L.J. Mullen, "Hybrid technique for enhanced optical ranging in turbid water environments," Optical Engineering, vol. 53, no. 5 (2014).

investigations have been performed to assess tradeoffs between dwell time and bandwidth compared to detection performance, indicating that dwell time and bandwidth can be reduced by 75% at a cost of less than 15% reduction in ranging performance. In summary, all techniques developed under this program have shown significant performance improvement potential in simulations and in laboratory-scale experiments.

Progress

Background

Hybrid lidar-radar ranging systems experience two main challenges from operating in the underwater channel that degrade system performance, as shown in Figure 1. The first of these is absorption, which occurs when a photon emitted from the laser is absorbed by water molecules or dissolved materials. Absorption causes the received signal level to decrease. The use of blue wavelengths in open ocean or green wavelengths in coastal ocean can be used to minimize absorption. The second challenge occurs due to scattering, in which photons are deflected out from the collimated laser beam after colliding with particles in the channel. Scattering degrades resolution and reduces range accuracy. Particularly challenging in the ranging application is the concept of backscattered photons, which are scattered backwards into the receiver field of view without reaching the desired object. If a sufficiently large amount of backscattered photons are collected, this may significantly reduce the probability of detection and increase the probability of false alarms. Scattering has typically been mitigated by applying high modulation frequencies to the laser as backscatter has been shown to have a lowpass frequency response [1,2]. In terms of backscatter reduction, ***this work applied digital signal processing algorithms to improve performance by processing the received signal rather than depending solely on the physics of the underwater channel.***

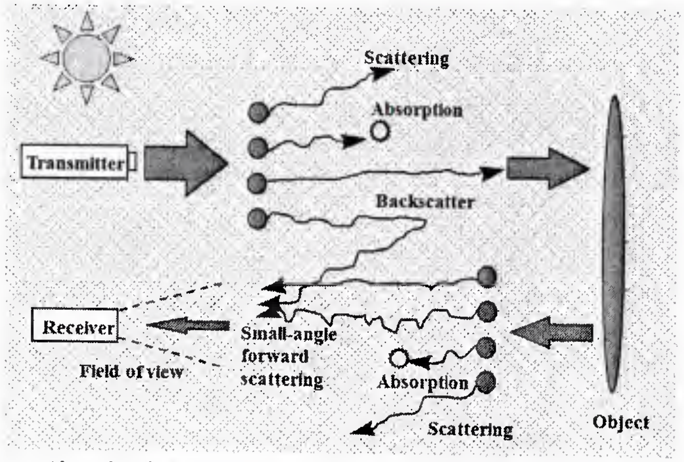

Figure 1. Sketch of water channel effects on hybrid lidar radar system

Although absorption and scattering are two separate physical phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient c, which has units of m^{-1}. Beam attenuation in water follows an exponential decay law

$$P(c,z) = P_0 e^{-cz}$$

where z is the distance to the object and P_0 is the transmitted signal power. The product cz in the exponent is referred to as the number of attenuation lengths (a.l.), which is a dimensionless parameter used to compare ranging performance in different water conditions and at different distances.

Baseline Ranging Approaches

This section will briefly discuss two previous ranging approaches developed by Laux et al. [3] that were evaluated in the beginning of this project and serve as a baseline for our work. These approaches both work by modulating the laser and measuring the phase shift between the transmitted and received signals to compute the range. In the single modulation frequency continuous wave hybrid lidar-radar approach (CW), the laser is modulated with a single frequency. As a result, the performance of this method is defined by the wavelength of this modulation frequency. This results in a number of tradeoffs, which are summarized in Table 1. CW ranging cannot simultaneously achieve high unambiguous range and high range precision. Additionally, there is a tradeoff between unambiguous range and backscatter suppression.

Table 1. Tradeoffs for single frequency CW method

Modulation frequency	Unambiguous range	Range precision	Backscatter suppression
Low	High	Low	Low
High	Low	High	High

The tradeoffs with the single frequency CW approach motivated the Navy to develop the dual frequency approach, in which the ranging performance depends on the difference between the two modulation frequencies. This allows the dual frequency approach to be operated with two modulation frequencies high enough to be above the backscatter cutoff point. The performance tradeoffs of this approach are summarized in Table 2. As with the single frequency CW approach, there is a tradeoff between high unambiguous range and high range precision.

Table 2. Tradeoffs for dual frequency method

Difference frequency	Unambiguous range	Range precision	Backscatter suppression
Low	High	Low	High
High	Low	High	High

The CW and dual frequency ranging techniques will serve as a baseline for new signal processing techniques that have been developed under this program. Each technique developed under this program will be summarized below with an

Technique #1: Delay Line Canceler – A Spatial Filtering Approach to Suppress Backscatter

The delay line canceler developed in FY12 will be briefly summarized. As previously mentioned, backscatter reduction is a critical stage in enhancing the usable range of any hybrid lidar-radar scheme that is deployed into a turbid underwater environment. In a highly scattering environment, many photons reaching the detector will have scattered off particulates in the water, while relatively few photons reaching the detector will have made the round-trip to and from the object of interest. This will cause the system to detect an object whose range is near the volumetric center of the scattering region, rather than the detecting the range to the object of interest. We adapted a delay line canceler from moving target indication (MTI) radar and through-the-wall radar imaging (TWRI), which deal with similar challenges in their applications. We derived the magnitude and phase responses of this filter for use in a turbid environment such as the underwater channel, where attenuation must be taken into consideration.

The spatial filtering approach operates on spatial frequencies rather than the electrical modulation frequency. For a system that only has one photodetector, the platform must be able to track the distance that it has traveled between measurements in order to apply the spatial filter. For systems above water or at shallow depth in calm waters, perhaps this could be achieved with high precision GPS. For systems in areas with strong currents, it would be very unlikely that the system could move an exact distance

between measurements without potentially substantial deviations caused by the system drifting in the water. For systems in deep waters, the system will not be able to receiver GPS due to the attenuation of the GPS signal by the water. A submerged platform with two photodetectors at an appropriate spacing avoids this issue but introduces new challenges associated with detector placement. For example, a system with two photodetectors should ideally place the detectors on an adjustable track so that the system could adapt the detector spacing to changes in modulation frequency or water conditions.

Experimental verification of this technique has been published in [4, 5]. In this work the delay line canceler was used with the single- and dual-tone approaches and experiments were performed in a 3.6 m long test tank at Patuxent River Naval Air Station. Results from these experiments are summarized in Table 3, which indicates performance in terms of attenuation lengths. In [7], experiments were performed with the delay line canceler applied to a single-tone system at 160 MHz, extending performance from 5.6 attenuation lengths out to 7.2 attenuation lengths. Experiments in [5] applied the delay line canceler to the dual frequency CW approach by applying a spatial filter independently to each modulation frequencies. Without applying the spatial filter, targets were detected out to approximately 5.7 attenuation lengths, while the spatial filter/dual frequency combination extended ranging performance out to 8.9 attenuation lengths. These results show that the spatial filter extends operating range by approximately 2-3 attenuation lengths by suppressing the backscatter return.

Table 3. Experimental Results using Delay Line Canceler

Technique	Attenuation lengths
Single-tone at 160 MHz	5.6
Delay line canceler at 160 MHz	7.2
Dual-tone at 140, 160 MHz	5.7
Delay line canceler at 140, 160 MHz	8.9

Approach #2: FDR – A New LIDAR Ranging Approach

In FY13, we adapted a technique from the fiber optic community known as frequency-domain reflectometry in order to overcome the unambiguous range and range precision tradeoffs affecting the dual-tone approach. The technique was adapted for underwater hybrid lidar-radar and simulations were performed in FY13. Simulations indicated a potential for centimeter-order accuracy and extended unambiguous ranging [6]. Experimental validation was obtained in FY14. The experimental setup and processing will be summarized before the results are presented.

The FY14 FDR experiments were performed in the 3.6 m tank at Patuxent River Naval Air Station, with results published in [7]. The experimental setup used to test the dual frequency and FDR ranging approaches is shown in Figure 2**Error! Reference source not found.**, with a photo of the setup shown in Figure 3**Error! Reference source not found.**. The output from a RF signal generator is combined with a DC source to modulate the current of a 442 nm laser diode. Modulated light was transmitted through a window onto a diffuse reflector target mounted on a translation stage. The target was moved in 10 cm increments from a range of 1.35 m to 3.05 m. The photomultiplier tube (PMT) collected light scattered from the submerged target through the window. A bias-tee at the output of the PMT separated the DC and AC components of the photocurrent. The DC-coupled signal was monitored on a multimeter to ensure that the PMT remained within its linear operating region. The AC-coupled signal was demodulated and digitized in the software defined radio (SDR) receiver. The I (in-phase) and Q (quadrature) samples obtained by the SDR were transferred over an Ethernet cable to a PC, where the data are processed in a custom LabVIEW program.

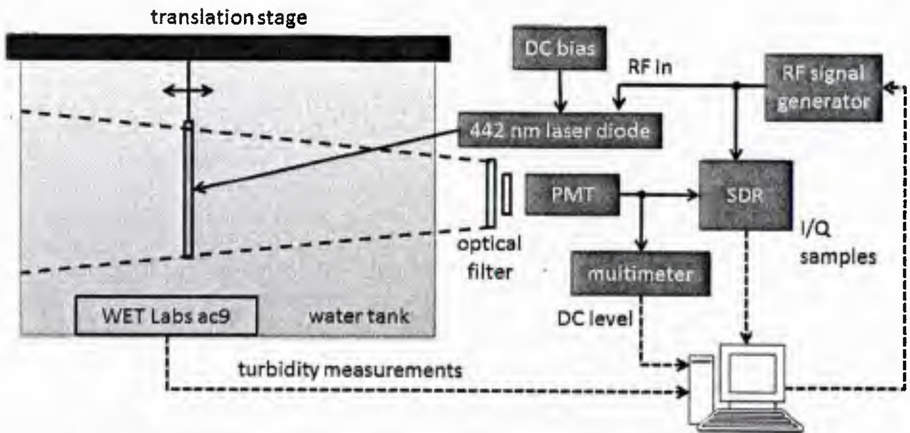

Figure 2. Block diagram of setup for FDR ranging experiments. A 442 nm laser diode is modulated with a stepped frequency waveform, modulated light is transmitted to an underwater object, and a PMT collects reflected light. The I/Q samples are generated by the SDR receiver and used to compute range on a PC.

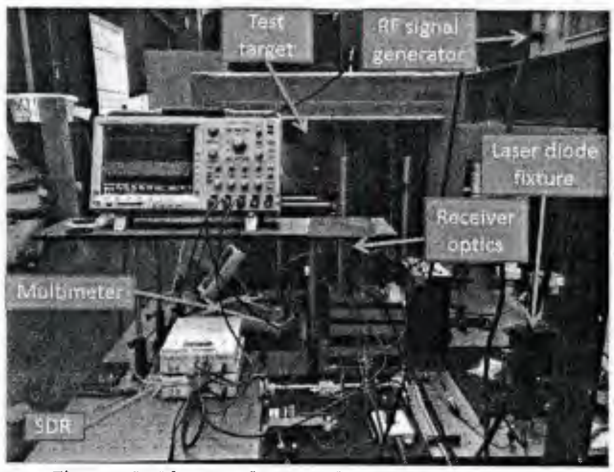

Figure 3. Photo of setup for FDR experiments

The key processing steps associate with the FDR method are shown in Figure 4. First, a stepped-frequency signal is transmitted into the channel, an example of which is shown in Figure 5. The unambiguous range depends on the frequency step size, while the theoretical limit on range accuracy depends on the bandwidth [6]. Once the signal has been demodulated and digitized, it is then processed with common DSP algorithms. The CORDIC (COordinate Rotation DIgital Computer) algorithm is used to perform a coordinate transform to convert the I and Q components of the return into amplitude and phase. The stepped waveform allows us to measure amplitude and phase at various frequencies, so that a complex frequency spectrum can be constructed. The frequency spectrum is used as the input to the inverse Fast Fourier Transform (IFFT), to obtain time-domain information indicating the time-of-flight to the target. This spectrum data enables the FDR technique to simultaneously detect both the desired object and the volumetric backscattering region. An automated peak detection algorithm can then determine which peak in the return corresponds to an object, and outputs the corresponding range position.

Figure 4. The FDR approach uses stepped frequency modulation and common DSP algorithms to compute range to an object.

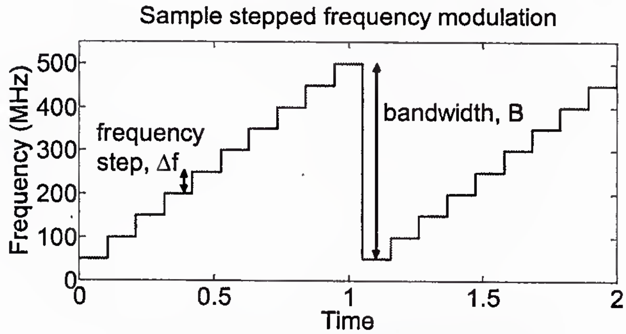

Figure 5. Sample stepped modulation

Ranging results from the FY14 FDR experiments and RangeFinder simulations are shown in Figure 6. The FDR configuration divided a 500 MHz bandwidth from 50 to 550 MHz into 128 equally spaced tones. A 400 MHz single frequency tone was used to enhance the range accuracy by smoothing out the "quantized range" calculated by FDR alone. In general, there is strong agreement between the simulated and experimental results. The simulated results suggest performance out to 10.8 attenuation lengths, while the experimental measurements obtained performance out to 10.2 attenuation lengths. The results can be qualitatively separated into two regions. In the first region, the FDR algorithm computes the range with range errors on the order of 3 cm. In the second region, beyond 10.2 attenuation lengths in the experimental data, the algorithm is no longer able to detect the target and instead returns the position of the backscatter. The observed sharp transitions are due to the peak detection algorithm being used in this work: when the target amplitude is less than the backscatter amplitude, the detection algorithm detects the center of the scattering region instead of the target. *However, it should be noted that the target is still evident in the range data even though it's amplitude drops below the backscatter amplitude. Therefore, additional performance is possible using a more sophisticated target detection algorithm.* To summarize, the FDR algorithm allows ranging out to 10.2 attenuation lengths, almost doubling the detection range previously achieved with the single- and dual-tone approaches.

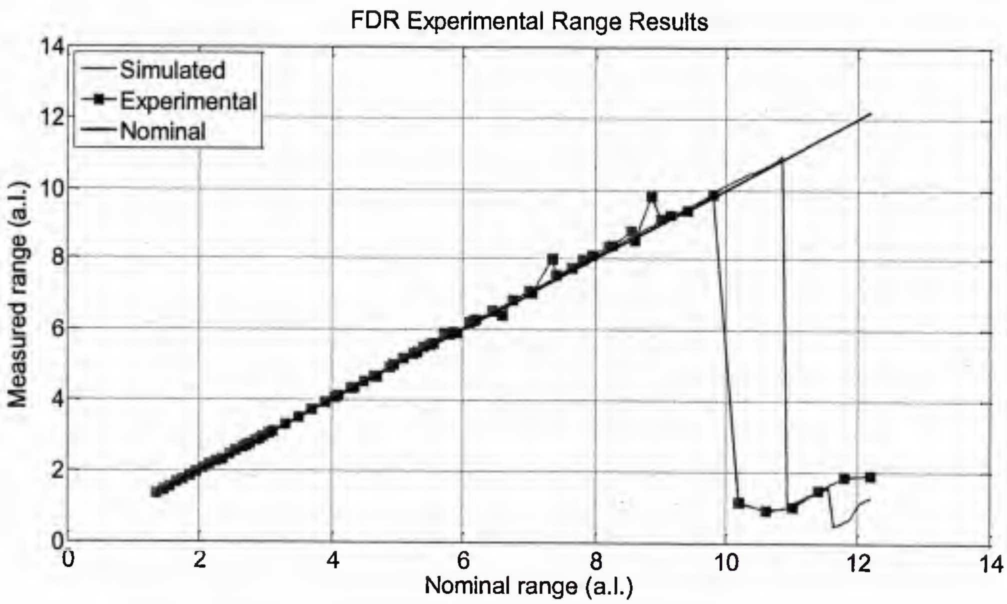

Figure 6. Simulated and experimental results for FDR ranging

Approach #3: Blind Signal Separation – Statistical Backscatter Suppression Technique

In FY13, the statistical digital signal processing technique of blind signal separation (BSS) was adapted to provide backscatter suppression for the FDR ranging approach. Experimental validation of this technique was obtained in FY14. In the BSS technique, data are transformed into a statistical domain in which signals are separated based on their statistical properties [8]. This is analogous to using the Fourier transform to transform data into the frequency domain and separate signals based on their frequency content. BSS does not need to be adjusted for every modulation frequency, which made it a more practical approach for backscatter suppression for the multiple frequencies required in the FDR method (as opposed to, for example, applying the delay line canceler to every FDR frequency). We will refer to the combined algorithm as FDR/BSS. Our implementation of BSS separates the target and backscatter returns based on the variances of their distributions, which is mathematically equivalent to performing an eigendecomposition to the data. The full signal processing approach for the FDR/BSS technique is shown below in Figure 7. The range profile output of the FDR algorithm (Figure 4) is taken as the input to the BSS algorithm. An eigendecomposition is performed using singular value decomposition, after which the eigenvalue corresponding to the backscatter component is set to zero. The adjusted eigenpairs are used to reconstruct a range profile, in which the backscatter is now suppressed. Finally, a peak detector is applied to return the range to the strongest peak in the FDR/BSS range profile.

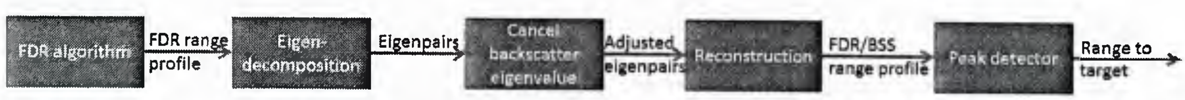

Figure 7. Block diagram of BSS technique

Theory, simulations, and experimental results for the FDR/BSS technique have been published in FY14 in [9]. The experimental setup was identical to the FDR setup, with BSS applied in post-processing. Range profiles for three cases are shown in Figure 8 to qualitatively demonstrate the backscatter suppression capability of the FDR/BSS technique compared to FDR alone. The nominal target positon is

marked on each profile in the three cases. In the object-limited case *(a)*, both FDR and FDR/BSS can easily detect the target position. In *(b)*, the turbidity has increased and a clutter return is now observed at short distances on the FDR range profile. Both algorithms are still able to detect the target position, with the clutter greatly reduced for FDR/BSS. Finally, in *(c)*, the turbidity is high enough that the FDR return is completely dominated by the clutter return. However, the FDR/BSS technique suppresses the backscatter enough that the target position can be detected in this scenario. This illustrates the capability for FDR/BSS to detect targets in what would otherwise be scatter-limited scenarios.

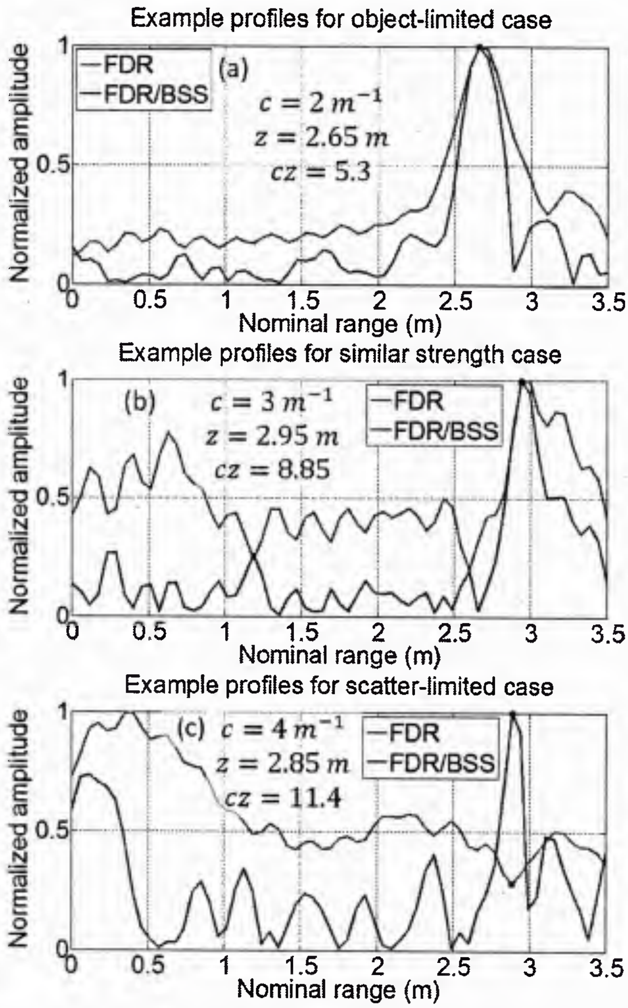

Figure 8. Range profiles for FDR/BSS and FDR algorithms for *(a)* object-limited, *(b)* similar strength, and *(c)* scatter-limited scenarios illustrating ability of FDR/BSS to suppress backscatter.

Simulated and experiment ranging results are shown below in Figure 9. In this case, the experimental results showed object tracking out to 14.7 attenuation lengths downrange, while the simulation predicts some degree of performance out to at least 18 attenuation lengths. In terms of range error, the mean range error in the object-tracking region of the experimental data is typically less than 3 cm. This indicates that FDR/BSS maintained comparable range error performance to FDR alone while extending the operating range by almost 5 attenuation lengths. As a result of the ability to suppress backscatter, FDR/BSS has a detection range almost three times as large as the single- and dual-tone approaches.

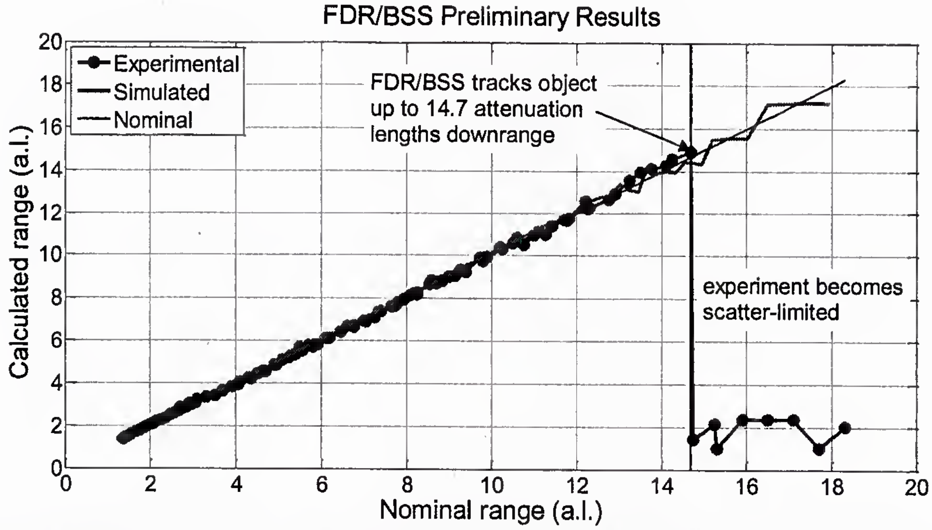

Figure 9. Ranging results for BSS experiment show object tracking to nearly 15 attenuation lengths downrange

A potential drawback with the FDR/BSS approach is the need to dwell on many frequencies across a large bandwidth. We have studied potential tradeoffs between reducing bandwidth and sweep time and the effect on ranging performance. Sweep time is defined by the number of tones in the sweep, as each tone is "dwelled on" for an equal amount of time. The primary configuration used to date has a bandwidth of 500 MHz and uses 128 tones corresponding to a 12.8 ms sweep time, with performance to 14.7 attenuation lengths. One promising result from the tradeoff study is shown below in FIGURE. In this FDR/BSS configuration, a 125 MHz bandwidth from 240 to 365 MHz was used with 32 tones corresponding to a 3.2 ms sweep time. The target was detected out to approximately 12.7 attenuation lengths before this configuration first detected the volumetric backscatter instead of the targe. Thus, a 75% reduction in bandwidth and sweep time, with only a 14% reduction in range performance was achieved. Reducing the number of tones lowers the sweep time, which in turn allows a system to make more measurements per second. The tradeoff study will help to optimize the FDR/BSS technique for deployment into a practical sensor platform.

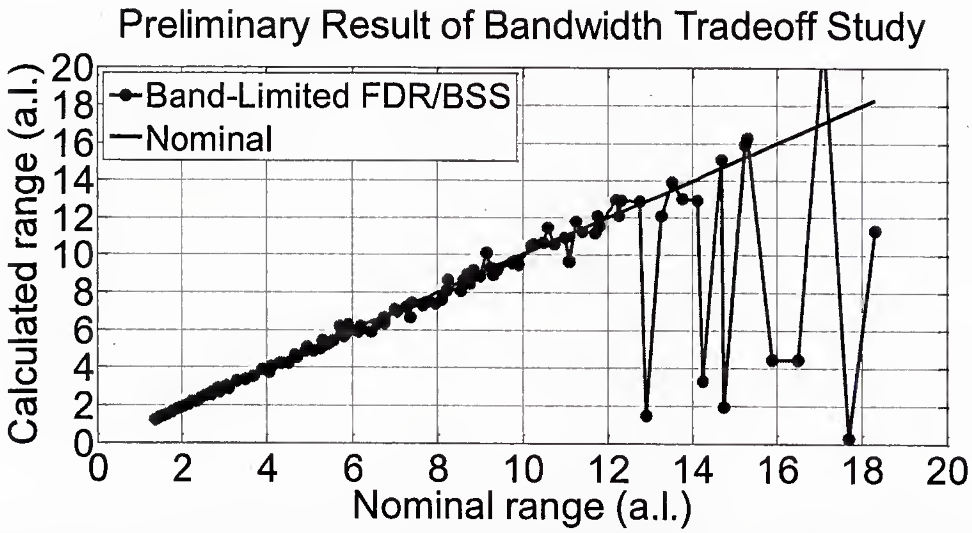

Figure 10. Tradeoff study configuration. A 75% reduction in bandwidth and sweep time resulted in a 14% reduction in ranging performance

Real-Time Digital Signal Processing

The second objective of this project is to deploy these ranging algorithms onto real-time digital signal processing (DSP) systems. Progress is summarized below in Table 4, where an X represents a completed task and the empty cells indicate remaining work. At this point the background information for each technique has been developed and large-scale tank experiments been performed for each technique. Real-time experiments have been performed for the single-tone, dual-tone, and FDR techniques with two different systems. A LabVIEW-based system at Patuxent River Naval Air Station has been used to perform real-time experiments for the single-tone and dual-tone techniques. This system uses the Ettus USRP (Universal Software Radio Peripheral) to perform pre-processing steps on raw data, with a PC running LabVIEW performing the final calculations to obtain range measurements.

A MATLAB-based system developed at Clarkson University in FY14 has been used to perform real-time FDR ranging experiments, as well as imaging experiments. The Clarkson experimental setup is shown below in Figure 11. A PC running MATLAB configures an RF signal generator to modulate a laser diode, which illuminates a target in a test tank. A PMT collects light reflected from the target. The AC component of the PMT output signal is mixed with a known reference signal, with the mixer output digitized. A DAQ (data acquisition) board is used to send the data to the PC, where range is calculated in the MATLAB program. This experimental setup can also be used to perform imaging experiments, in which an Arduino microcontroller board is used to control a laser scanner. A MATLAB program collects data at each pixel and constructs both amplitude and range images.

Table 4. Summary status of ranging algorithms

		Single-tone	Dual-tone	FDR	Single-tone + spatial filter	Dual-tone + spatial filter	FDR/ BSS
Background	Theory	X	X	X	X	X	X
	Simulation	X	X	X	X	X	X
Experimental	Proof-of-concept	X	X	X	X	X	X

Investigation	Small-scale (benchtop)	X	X	X	X	X	X
	Large-scale (tank)	X	X	X	X	X	X
Real-Time Implementation	Code design	X	X	X	X	X	X
	Simulation	X	X	X			
	Implementation	X	X	X			
	Real-time experiment	X	X	X			

A next step will be to deploy the algorithms into embedded platforms to eliminate the dependency on external PCs. Designs for Xilinx-based FPGA platforms have been developed for several algorithms and will be deployed to FPGA platforms in future experiments. The supporting hardware should also be miniaturized to develop a more compact sensor, for potential future deployment into unmanned underwater vehicle platforms.

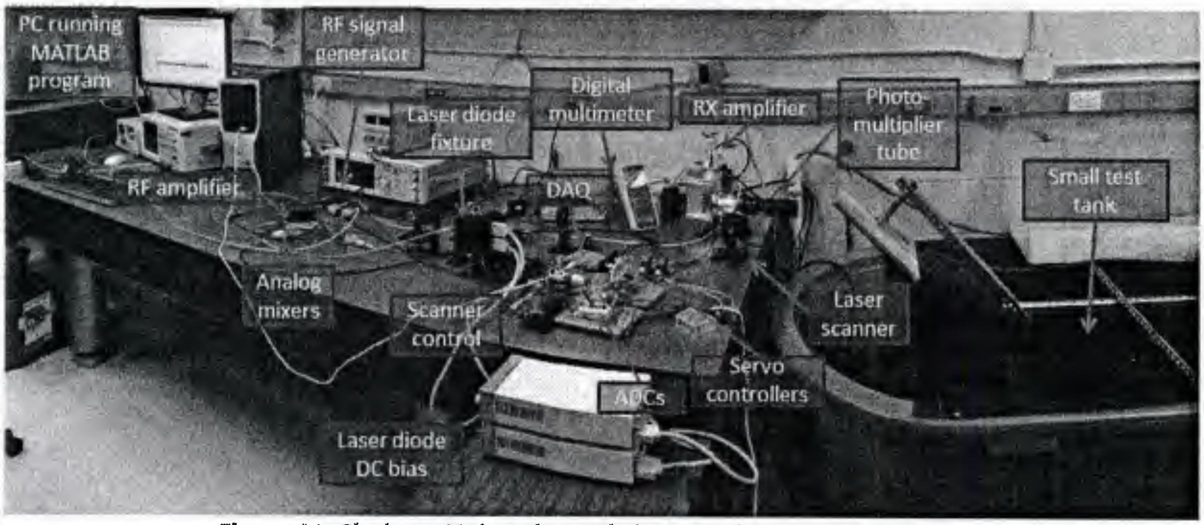

Figure 11. Clarkson University real-time ranging experiment setup (ADC: analog-to-digital converter, DAQ: data acquisition board)

Summary of new FDR/BSS ranging approach

The new ranging approaches developed in this project were designed to perform automatic target detection without requiring input from a human operator. To summarize the major processing steps:

- Frequency-domain reflectometry allows a high unambiguous range measurement of the composite target and backscatter return
- Blind signal separation performs a statistical separation to extract the target return from the composite return signal by essentially filtering out the backscatter return
- Inverse Fourier Transform converts the filtered return signal into an instantaneous range spectrum
- Peak detection detects the range to the target

In scenarios where the FDR sweep is unable to achieve the desired precision due to bandwidth limitations, an optional fifth step can be performed in which a single modulation frequency CW approach may be used to obtain finer precision ranging information following the peak detection step. Work is on-going to quantify the effects of reduced bandwidth and sweep time on ranging performance.

Project Summary

Several digital signal processing techniques to enhance the performance of underwater hybrid lidar-radar ranging systems have been developed and validated under this project. Results obtained with each technique are summarized below in Table 5, which also indicates theoretical ranging performance in open ocean and harbor waters for each technique. The first two entries of Table 5 are the baseline single-tone and dual-tone approaches that were previously developed by the Navy. The remaining table entries summarize the techniques developed under this program. The developed techniques have enhanced the ability to separate the target and backscatter components of underwater lidar return signals, enabling targets to be detected at increasingly longer distances. The experimental and simulated results show that thFDR/BSS approach can increase the ranging distance by a factor of ~2.6 compared to the single-tone approach. *However, it should be noted that additional FDR/BSS performance may be possible using a more sophisticated target detection algorithm since the target is still evident in the range data – the current peak detection algorithm simply detects the highest peak. Therefore, once the target amplitude drops below the volumetric backscatter amplitude the peak detection algorithm declares the volumetric backscatter to be the target.* Significant progress has been made in developing a digital signal processing approach to enable hybrid lidar-radar ranging systems to perform accurate automatic target detection at extended ranges.

Table 5. Summary of Range Performance*

Processing Technique	Attenuation lengths	Open ocean (m)	Harbor Conditions (m)	Average Range Improvement Factor
Single-tone (baseline)	5.6	56	2.8	1.00
Dual-tone (baseline)	5.7	57	2.9	1.03
Single-tone with spatial filter	7.2	72	3.6	1.29
Dual-tone with spatial filter	8.9	89	4.5	1.60
FDR	10.2	102	5.1	1.82
FDR/BSS	14.7	147	7.4	2.63

*Performance in real waters may vary from test tank results.

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